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GEOLOGICAL SURVEY PROFESSIONAL PAPER 1067-E

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By R. B. MIXON, B. J. SZABO, *and* J. P. OWENS

SURFACE AND SHALLOW SUBSURFACE GEOLOGIC STUDIES IN THE EMERGED COASTAL PLAIN OF THE MIDDLE ATLANTIC STATES

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A tentative stratigraphic framework for late Pleistocene deposits of the southern Chesapeake Bay area is used as a basis for evaluating uranium-series dates from fossil corals and mollusks

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By R. B. MIXON, B. J. SZABO, and J. P. OWENS

ABSTRACT

Geologic mapping in conjunction with uranium-series dating of fossil mollusks and corals suggests that the low-lying (< 17 m in altitude) terrace deposits in the central and southern Chesapeake Bay area include two main depositional sequences, each of which represents a high stand of the sea in late Pleistocene time. The older depositional sequence includes the Accomack and Omar beds of the Delmarva area, the fossiliferous deposits along the lower Rappahannock River, and the Norfolk Formation deposits *west* of the Suffolk scarp. These beds have yielded a single reliable coral age estimate of 184,000 ± 20,000 years B.P., suggesting an early late Pleistocene age. The younger sequence, including the type beds of the Norfolk Formation and equivalent strata *east* of the Suffolk scarp, has yielded several coral ages ranging from about 62,000 to 86,000 years B.P. (including ages from our samples and previously reported age estimates); thus, it is clearly late Pleistocene in age. Groupings of ages obtained from our quahog analyses also suggest two transgressive sequences; however, the estimated quahog ages are consistently younger than ages based on coral samples from the same and equivalent stratigraphic units.

Stratigraphic, paleoclimatic, and geomorphic data suggest that the estimated uranium-series age of 71,000 ± 7,000 years B.P. for the type beds of the Norfolk, obtained by averaging our coral dates, may be too young by as much as several tens of thousands of years. A postulated equivalency of the type Norfolk beds, upper Pleistocene deposits near Charleston, S.C. (apparent uranium-series age = 95,000 ± 5,000 years), and deposits in the Caribbean area thought to represent the highest sea stand during the last interglacial period (apparent age, 125,000 ± 10,000 years) implies diagenetic modification of coralline material possibly in part because of regional differences in depositional and postdepositional environments.

INTRODUCTION

The Chesapeake Bay, one of the world's largest estuaries, is bordered by extensive low-lying terrace deposits of marine and estuarine origin that record fluctuations of sea level and episodes of erosion and deposition during Pleistocene and Holocene time (pl. 1). The terrace deposits have been the subject of several recent studies concerned with reconstructing the geologic history of the bay region (Oaks and Coch, 1973; Mixon and others, 1974; Johnson, 1972, 1976; Owens and Denny, 1978, 1979a, b). These studies have emphasized (1) the identification and definition of rock-stratigraphic units (formations) on the basis of surface mapping and borehole data and (2) the interpretation of depositional environments represented by the various lithic units. Within each study area, the continuity and relative ages of rock units, as determined by lithic and faunal similarities and truncating relationships, have been fairly well established. However, correlations of terrace deposits from one side of Chesapeake Bay to the other, or even across lesser estuarine drainages, such as the James River, are based mainly on comparison of similar stratigraphic sequences and geomorphic relationships. The uranium-series dating of corals and mollusks for this study was initiated to provide better estimates of the absolute age of the deposits and to help establish a time-stratigraphic framework to aid in the regional correlation of the coastwise terrace deposits.

Because of the paucity of coralline material in the Chesapeake Bay area and the need to obtain a better stratigraphic and geographic spread of analytical data, we found it necessary to supplement the few available coral samples with both mollusk and bone materials. Our report[1] evaluates the reliability of the uranium-series ages obtained from the mollusk and bone data by comparing these ages with our stratigraphic data, with radiocarbon dates from wood, and with uranium-series dates from coral.

[1] The object of this study is to evaluate uranium-series ages on the basis of the regional stratigraphic framework as presently known. Thus, we have not formally established new lithic units or redefined old ones. In some places, we have proposed alternative definitions of lithic units and stratigraphic relationships, but we recognize that further detailed mapping is needed to resolve differences in interpretation.

GEOLOGIC SETTING

The upper Cenozoic stratigraphic section in the study area consists of unconsolidated sand, gravel, silt, and clay of Quaternary age, generally less than 30 m thick, that unconformably overlie much thicker and more consolidated strata of Pliocene and Miocene age (Yorktown Formation, Beaverdam Sand, and older units; see Oaks and Coch, 1973, p. 47–51; Owens and Denny, 1979b, p. A7–A15). The Quaternary beds include the Holocene and uppermost Pleistocene fills of Chesapeake Bay (Hack, 1957) and a series of low-lying (<17 m in altitude) terrace deposits of older Pleistocene age that border the bay and its major tributaries. A Holocene barrier-island and lagoon complex, as much as 13 km wide, borders the ocean side of the Delmarva Peninsula and the coastal part of the Norfolk area, Virginia (Kraft, 1971).

The terrace deposits, subject of the present study, underlie a series of flat to gently rolling surfaces, separated by low scarps, which step down toward the Chesapeake Bay and the Atlantic coast from older highlands to the west and north. The generalized geologic map (pl. 1) showing the distribution and relative age of the terrace deposits and older lithic units in the study area is based mainly on our mapping in the Delmarva Peninsula (Owens and Denny, 1978, 1979a; Mixon, unpublished data), that of Oaks and Coch (1973, pls. 1 and 2) in the Norfolk area, and that of Johnson (1972, pls. 1–3; 1976, pls. 1–3) in the peninsula area between the James and York Rivers. Except for some detailed stratigraphic work near the mouth of the Rappahannock River (W. L. Newell, U.S. Geological Survey, unpublished data, 1979) and palynologic studies at the classic Wailes Bluff locality on the lower Potomac River (Thompson, 1972), the terrace deposits north of the York River have been studied only in reconnaissance.

The distribution and age relationships of lithic units composing the terrace deposits, as shown on our geologic map, follow closely the interpretations of the published stratigraphic studies, except in parts of the Norfolk area, Virginia, mapped by Oaks (contrast our map, pl. 1, with the map of Oaks and Coch, 1973, pl. 2). As many of our uranium-series ages are from samples collected from the Norfolk and Kempsville beds in the Norfolk area, differences between the distribution and relationships of these units as originally defined by Oaks and Coch (1973) and our suggested modifications (this report) are discussed briefly in the following text.

We are in basic agreement with Oaks' interpretation of the stratigraphy of the Norfolk and Kempsville Formations in the type area of these units south of Norfolk (Womack borrow pit, pl. 1, fig. 1, loc. 11). Oaks' detailed geologic section through the Fentress rise and Hickory scarp in this area shows two superposed rock-stratigraphic units of marginal marine origin (Norfolk and Kempsville Formations) that are traceable across the Hickory scarp and two younger units (Sand Bridge and Londonbridge Formations of Oaks and Coch, 1973) that underlie a relict marine plain (Mount Pleasant flat) east of the scarp (see Oaks and Coch, 1973, fig. 24, section II–II′; this report, fig. 2*A*). However, south of the type area, the Kempsville is mapped as a linear body of beach and dune sand and surficial marsh deposits that truncates and laps onto older deposits (Norfolk Formation) of the Fentress rise and grades eastward, in the subsurface, into thin nearshore-shelf deposits (Oaks and Coch, 1973, fig. 24, section JJ–JJ′, and pl. 2, sections AA–AA′ to GG–GG′; see also this report, fig. 2*B* and pl. 2, sections A, B). Thus, the distribution of the Kempsville Formation as defined by Oaks (*in* Oaks and Coch, 1973) is restricted to a relatively narrow striplike area along and adjacent to the Hickory scarp.

An alternative interpretation of the Kempsville beds, based in part on extensive exposures of the Kempsville in a borrow pit excavated deeply into the Fentress rise (New Light pit, pl. 1, loc. 10), is that the well-sorted, crossbedded Kempsville sand underlying the eastern part of the Fentress rise represents deposits of a barrier-island complex rather than beach and dune deposits along a mainland shoreline, as proposed by Oaks and Coch (1973, fig. 25). In this interpretation, the medium to coarse Kempsville sands along and near the Hickory scarp are coeval with fine-grained backbarrier deposits extending westward to the Suffolk scarp. Thus, all or parts of units *west* of the Hickory scarp included in the Londonbridge and Sand Bridge Formations by Oaks and Coch (1973, p. 84–97) are here considered to be lagoonal and estuarine equivalents of the Kempsville Formation and are mapped with that unit (compare Oaks and Coch, 1973, pls. 1 and 2, with pls. 1 and 2 of this report). The upper part of unit Qn_8 of the Norfolk Formation of Oaks and Coch in the Fentress rise area, which is adjacent on the west to the "type" Kempsville beds, should also probably be included in the Kempsville Formation (pl. 2, this report). It follows that we would restrict the Sand Bridge Formation to the area north of the Diamond Springs scarp and east of the Hickory scarp (pl. 1).

We emphasize that the proposed expansion of the definition of the Kempsville Formation to include extensive backbarrier deposits west of the Fentress rise is based mainly on the interpretation of paleoenvironments and stratigraphic relationships of the well-exposed Kempsville sections in the New Light pit area that were not available to Oaks and Coch at the time of their study. To us, the lithologies, sedimentary structures, and fossils of the Kempsville beds in the New Light area fit beautifully a model of barrier-island sands, including very nearshore shelf, tidal-delta, and wash-

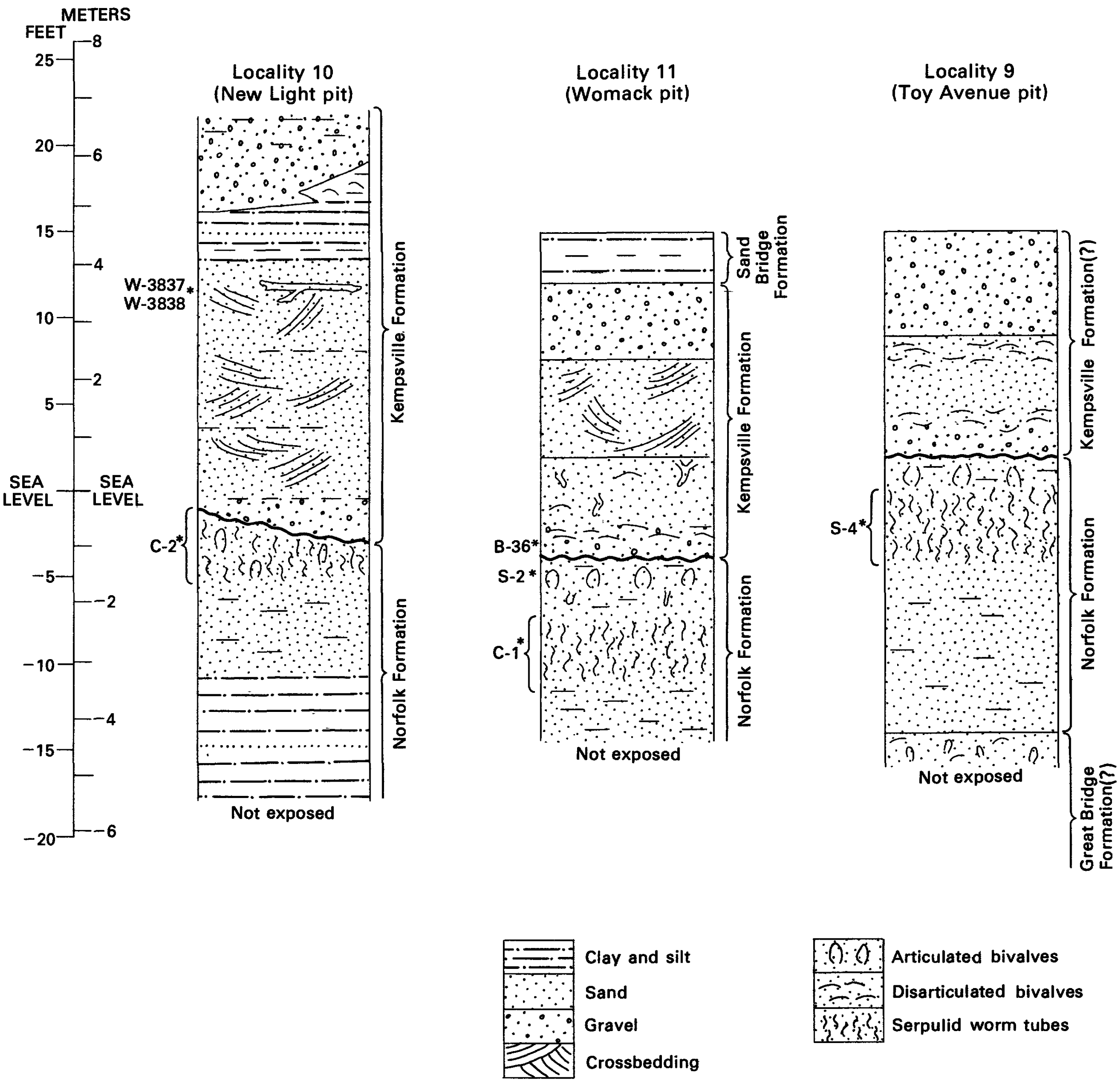


FIGURE 1.–Sections of Great Bridge(?), Norfolk, Kempsville, and Sand Bridge Formations of Oaks and Coch exposed in borrow pits in Norfolk area, Virginia. Sections in Womack and Toy Avenue pits modified from Valentine (1971). Asterisks show approximate horizons at which samples of corals (C-1 and C-2), mollusks (S-2 and S-4), bone (B-36), and wood (W-3837, W-3838) were collected for uranium series and radiocarbon dating. Sample numbers refer to tables 1-3. Locality numbers refer to plate 1.

over-fan deposits, that grade upward and westward into silty sand and clayey silt of backbarrier origin. However, further detailed mapping and drilling is needed to determine conclusively whether "Sand Bridge" and "Londonbridge" beds between the Hickory and Suffolk scarps (pl. 1) should be included in the Kempsville.

Another major unresolved problem in the Norfolk area is the time relationship of the fossiliferous Norfolk beds of the type area (Womack pit and vicinity) to surficial beds along and west of the Suffolk scarp that are mapped as units Qn_1, Qn_2, and Qn_3 of the Norfolk Formation (Oaks and Coch, 1973, pls. 1 and 2; this report, pl. 2). Oaks and Coch have mapped the type Norfolk beds and the "Norfolk" beds west of the scarp as time equivalents. However, the very shallow shelf depositional environment inferred for the type Norfolk beds and the apparent inset of the type Norfolk well below relict depositional surfaces at the top of "Norfolk" beds along and west of the Suffolk scarp (units Qn_1, Qn_2, and Qn_3) suggest to us that the Norfolk beds of marine origin

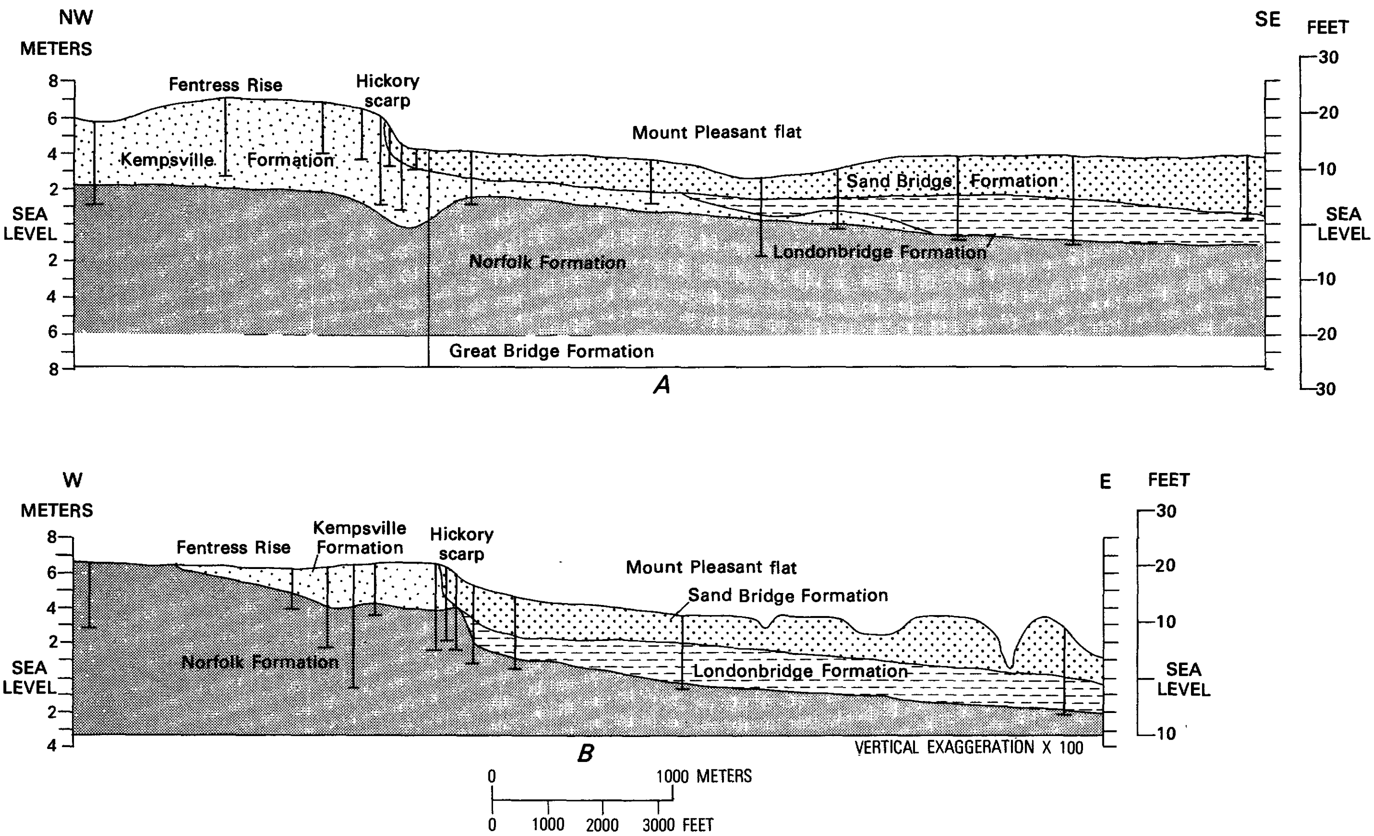


FIGURE 2.—Detailed geologic cross sections through Hickory scarp in the Norfolk area, Virginia, showing the interpretation of Oaks and Coch (modified from Oaks and Coch, 1973, fig. 24). Boreholes shown by vertical lines.

east of the Suffolk scarp may be more closely related in time to the Kempsville than to the "Norfolk" beds of fluvial, estuarine, and lagoonal origin *west* of the scarp. The latter interpretation is supported by our uranium-series age estimates (see discussion of "Age of deposits"). As is true for the Kempsville Formation, further stratigraphic work is needed to clarify relationships across the Suffolk scarp of beds mapped by Oaks and Coch as different lithofacies of the Norfolk.

A tentative correlation of rock-stratigraphic units of late Pleistocene age in the vicinity of Norfolk and elsewhere within the study area is given in figure 3. These lithic units may be grouped into three, or possibly four, depositional sequences, including, from oldest to youngest: (1) the Accomack and Rappahannock River beds and "Norfolk" Formation beds *west* of the Suffolk scarp; (2) the type beds of the Norfolk Formation of Oaks and Coch and equivalent strata *east* of the Suffolk scarp; (3) the Kempsville Formation of Oaks and Coch and the Sedgefield[2] and Occohannock beds; and (4) the Sand Bridge Formation[3], Kent Island Formation, and Lynnhaven[2]-Poquoson[2] beds (see pl. 1, fig. 3). If the Norfolk beds and the Kempsville Formation should represent transgressive and regressive phases, respectively, of the same depositional cycle, the low-lying terrace deposits in the southern Chesapeake region would include only three mappable sequences.

In updip areas, deposits of each of the foregoing sequences are commonly separated from those of adjacent sequences by unconformities and (or) truncating relationships at bounding scarps. Thus, in our interpretation, the Hickory, Big Bethel, and Pungoteague scarps are the updip limits, respectively, of the Sand Bridge, Lynnhaven-Poquoson, and Kent Island beds (see pl. 1). Similarly, the Suffolk, Harpersville, and Cheriton scarps are the updip limit of the Kempsville-Sedgefield-Occohannock sequence. The older "Norfolk" beds and equivalent strata appear to be bounded on the west and north by the Hazelton and Lee Hall scarps (see Oaks and Coch, 1973, p. 17; Johnson, 1972, p. 7–11). Conversely, the "older" Norfolk beds extend eastward in the subsurface beneath the Suffolk and Harpersville scarps, and the type Norfolk beds and the Kempsville are present seaward from the Hickory scarp (Johnson, 1976, pl. 2; this report, fig. 2). These relationships indicate fluctuations of sea level and erosional intervals of uncertain extent and duration.

[2]Sedgefield, Lynnhaven, and Poquoson Members of the Tabb Formation of Johnson (1976).
[3]Sand Bridge Formation of Oaks and Coch (1973, restricted).

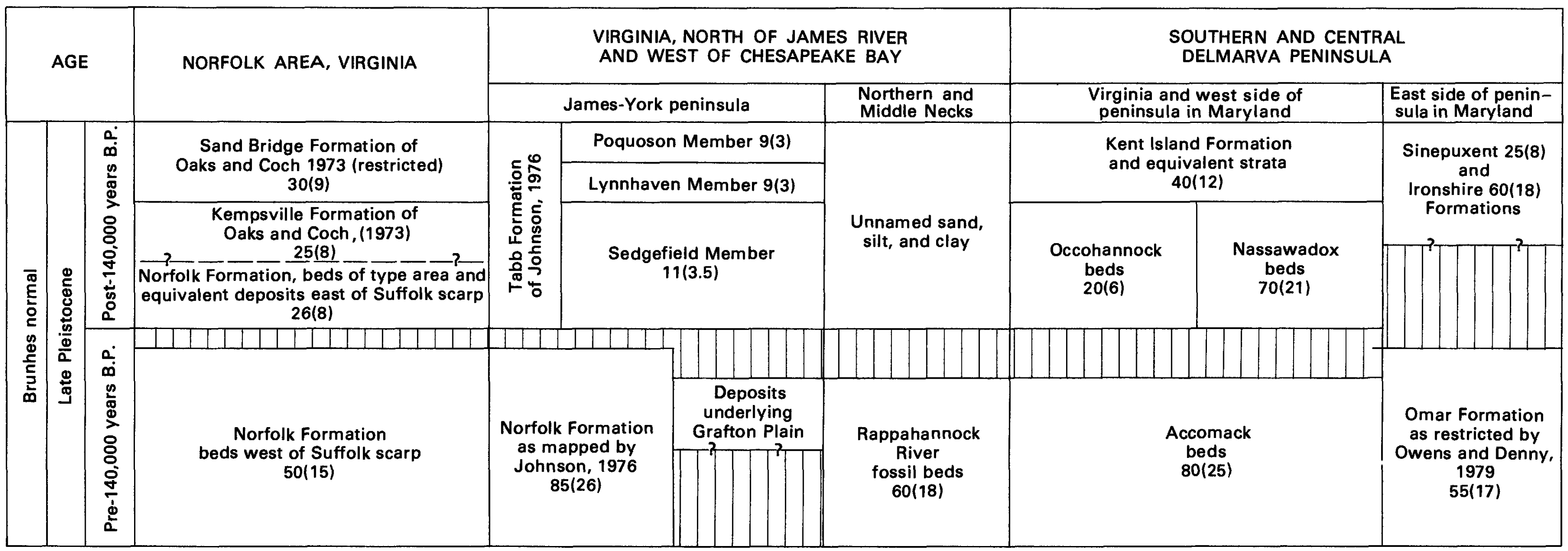


FIGURE 3.—Tentative correlation and thickness of Pleistocene rock-stratigraphic units in southern and central Chesapeake Bay area, Virginia and Maryland. Numbers show maximum thickness of units in feet (meters). Units vary greatly in thickness within short lateral distances and may pinch out both updip and downdip.

A determination of the *relative* age of the terrace deposits has been necessary in order to reconstruct the geologic history of the Chesapeake Bay region. However, as fossil species in these deposits are extant, the traditional biostratigraphic approach of comparing faunal and floral assemblages has not been definitive. Instead, relative age determinations have depended locally on the law of superposition and subregionally on comparisons of stratigraphic sections and geomorphic relationships and the establishment of similar sequences of geologic events. The *absolute* age of the deposits and, by inference, the amount of time represented by erosional intervals marked by regional unconformities and scarps are the subjects of widely differing interpretations (see, for example, Belknap, 1979, and Johnson, 1976).

LABORATORY METHOD AND SAMPLING PROCEDURE

DISCUSSION OF METHOD

The uranium-series dates for this study were obtained by measuring the amounts of the nuclides ^{230}Th and ^{231}Pa that are produced through time by their respective radioactive parent elements, ^{234}U and ^{235}U (Szabo, 1969). The method assumes that the sample initially absorbs uranium but no thorium or protactinium and that it subsequently neither gains nor loses any amount of these three elements. Coral has proved to be the most suitable material for this type of dating because the skeleton assimilates uranium throughout the organism's life cycle but, after death, is a closed system with respect to ^{230}Th, ^{231}Pa, and uranium isotopes. On the other hand, mollusks may yield unreliable age estimates because absorption of uranium takes place after the death of the animal and continues for an unknown length of time. Erratic results are especially predictable if large amounts of ^{232}Th, suggesting extraneous ^{230}Th and ^{231}Pa, and (or) evidences of isotopic migration patterns contrary to ideal closed-system conditions are observed (Szabo and Rosholt, 1969; Kaufman and others, 1971; Szabo and Vedder, 1971). Some mollusks, however, yield concordant ^{230}Th and ^{231}Pa dates that are in excellent agreement with coral dates from the same fossiliferous horizon (James and others, 1971; Szabo, 1979).

Uranium emplacement in fossil bones is also a secondary process that continues until all active organic matter is decomposed. Ideal closed-system conditions in bone are commonly violated; therefore, obtaining both ^{230}Th and ^{231}Pa dates for each sample is useful for meaningful evaluation of closed-system assumptions (Szabo and others, 1969; Szabo and Collins, 1975).

SELECTION AND STRATIGRAPHIC DISTRIBUTION OF SAMPLES

Because coral is much less common in the Pleistocene deposits of the Chesapeake Bay area than it is in the southeastern Atlantic Coastal Plain or the Caribbean region, we have collected and analyzed coral samples from only five localities (see table 1, pl. 1). However, the age estimates provided by these corals and the coral ages previously reported by Oaks and Coch (1973) are the "golden spikes" on which the time-stratigraphic framework for the Pleistocene deposits of the bay area is based. To supplement the few available coral samples, we have also analyzed 19 mollusks and one porpoise vertebra. The 15 sample localities are shown on plate 1.

The coral samples include three specimens of *Astrangia* from the type area of the Norfolk Formation of Oaks and Coch, abundant large unabraded fragments of *Oculina* from a single locality in the Accomack beds, and an *Astrangia* from unnamed fossil beds on the lower Rappahannock River that we consider to be correlative with the Accomack beds.

The porpoise vertebra is from the basal beds of the Kempsville Formation.

The mollusk samples include 13 specimens of the quahog *Mercenaria* sp., five specimens of the common edible oyster *Crassostrea virginica*, and one gastropod *Busycon* sp. Quahogs and oysters were chosen for analysis because of their relative abundance and wide stratigraphic and geographic distribution. The large size and generally good preservation of shell material was also a factor in selection of these species. Where possible, specimens that had articulated valves in growth position were collected to minimize the chance of analyzing reworked material. Most of the quahog samples were collected from the type beds of the Norfolk Formation of Oaks and Coch, the Accomack beds of the Delmarva Peninsula, and the fossil beds on the Rappahannock River and at Wailes Bluff thought to be equivalent to the Accomack.

The Kempsville[4]–Sedgefield–Occohannock sequence yielded very sparse fossil material suitable for uranium-series dating, possibly because these surficial units are relatively thin and generally consist of very permeable sandy sediment subject to extensive leaching. No quahog or coralline material from the Sand Bridge–Lynnhaven–Poquoson–Kent Island sequence was available for uranium-series dating.

[4]Some disagreement as to the placement of the Norfolk-Kempsville boundary at the type locality of these units (Womack pit, pl. 1, loc. 11) has been pointed out by Belknap (1979, p. 465). Valentine (1971, p. D11, D25–D26) placed the boundary at the base of a discontinuous, medium to coarse gravelly sand containing abundant bones of seals, walrus, and other cool-climate vertebrates. An underlying 0.5- to 1-m-thick bed of fine to coarse sand containing abundant articulated *Mercenaria* sp. and other fossils was included in the Norfolk Formation of Oaks and Coch. In contrast, Paul Drez (see Ray and others, 1968) and Oaks and Coch (1973, p. 123) included the bed that contained the articulated *Mercenaria* in the basal part of the Kempsville. We have followed the example of Valentine in placing the Norfolk-Kempsville boundary at the base of the discontinuous gravelly sand. Thus, coral ages reported from the Kempsville (Oaks and others, 1974, p. 75) from *Astrangia* sp. encrusting articulated *Mercenaria* sp. are probably from beds that we would include in the Norfolk.

TABLE 1.—*Analytical data and uranium-series ages of corals from the Chesapeake Bay area, Virginia*

Sample[1] No.	Locality[2] No.	Stratigraphic unit	Uranium (ppm)	Thorium (ppm)	Isotopic-activity ratios: $^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	$^{231}Pa/^{235}U$	Calculated age (10^3 years B.P.): ^{230}Th[3]	^{231}Pa[4]	Estimated age (10^3 years B.P.)
C-1	11. Womack pit.	Norfolk Formation of Oaks and Coch (type locality).	[5]4.52±.04	[5]0.44±.02	1.09±.02	0.436±.017	15.	0.75±.05	60±4	64±8	62±2
C-2	10. New Light pit.	Norfolk Formation of Oaks and Coch.	[5]4.71±.05	[5].31±.01	1.10±.02	.500±.020	25.	Not done	73±4	Not done	73±4
C-3	14. Norris Bridge.	Rappahannock River beds.	[6]4.06±.08	[6].99±.05	1.06±.02	.832±.033	11.	Not done	184±20	Not done	184±20
C-4a	3. Mathews' Field.	Accomack beds	[6]3.81±.08	[6]1.6 ±.2	1.05±.02	1.13 ±.040	8.5	Not done	Not applicable	Not applicable	None
C-4b	do	do	[6]3.61±.07	[6].52±.05	1.06±.02	.975±.039	21.	Not done	341^{+139}_{-66}	Not applicable	341^{+139}_{-66}
C-18	12. Mears Corner.	Norfolk Formation (?)	[6]4.36±.09	[6].32±.05	1.11±.02	.524±.021	24.	Not done	79±5	Not done	79±5

[1] Samples 1, 2, 3, and 18 are *Astrangia* sp.; sample 4 is *Oculina* sp.; all samples contain less than 3 percent calcite.
[2] Number refers to pl. 1.
[3] Corrected for unsupported ^{230}Th: $(^{230}Th)_0 = 0.67\ ^{232}Th\ e^{-\lambda_{230}t}$; calculated using half-lives of ^{230}Th and ^{234}U of 75,200 and 244,000 years, respectively.
[4] Corrected for unsupported ^{231}Pa: $(^{231}Pa)_0 = 0.67\ ^{232}Th\ e^{-\lambda_{231}t}$; calculated using half-life of ^{231}Pa of 32,500 years.
[5] Determined by mass spectrometry; reported as CaO.
[6] Determined by alpha spectrometry; reported as CaO.

SAMPLE PREPARATION AND LABORATORY PROCEDURE

The samples analyzed for this study were first checked by X-ray diffraction for possible recrystallization of original aragonitic (corals, quahogs, and gastropods) and calcitic (oysters) skeletal material. After being cleaned by scraping and ultrasonic scrubbing in water, the samples were crushed to a fine powder, homogenized, and ignited at 900°C for about 8 hours. Uranium and thorium concentrations of most samples were determined by mass spectrometric analysis using enriched ^{235}U and ^{230}Th spikes; samples C-3, C-4a, C-4b, C-18, S-29, and S-30 were determined by alpha spectrometry using ^{236}U and ^{229}Th spikes. The $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ activity ratios were determined by alpha spectrometric analysis using a combined ^{229}Th and ^{228}Th spike (Szabo and Rosholt, 1969; Rosholt and others, 1966). The $^{231}Pa/^{235}U$ activity ratios were determined by thermal neutron-activation analysis and alpha spectrometry (Rosholt and Szabo, 1969).

RESULTS OF ANALYSES

The results of analyses and calculated ^{230}Th and ^{231}Pa ages for each sample are shown in tables 1–3. The data for corals, quahogs, and oysters are grouped and discussed separately because of the different skeletal characteristics and different behavior of the skeletal material with respect to gain or loss of uranium and uranium daughters. For convenience, the bone and gastropod analyses are included with that of the oysters in table 3.

CORAL SAMPLES

Our coral samples include two specimens of *Astrangia* sp. obtained from outcrops of the Norfolk Formation of Oaks and Coch in borrow pits in the type area near Norfolk, Va. (table 1, samples C-1, C-2; fig. 1). Averaging the calculated ^{230}Th and ^{231}Pa dates for sample C-1 provides an estimated age of 62,000±2,000 years B.P. for the Norfolk beds at this locality (Womack pit). The ^{230}Th age for sample C-2 from the nearby New Light pit is 73,000±4,000 years B.P.; no protactinium date was calculated. A third coral sample (C-18) obtained from a pit near Mears Corner (loc. 12), about 2 km southwest of the Womack and New Light pits, is thought to be from strata equivalent to the type Norfolk beds and yields an estimated ^{230}Th age of 79,000±5,000 years B.P. These age estimates are in close agreement with previously reported coral ages from the Norfolk Formation of Oaks and Coch ranging from 62,000 to 86,000 years B.P. (Oaks and Coch, 1973, p. 79).

Another specimen of *Astrangia* sp. (sample C-3, loc. 14) is from unnamed fossiliferous strata along the lower Rappahannock River (fig. 4) that are considered to be correlative with the Accomack beds of the southern Delmarva Peninsula directly across the bay. The calculated ^{230}Th age of 184,000±20,000 years B.P. for this sample is especially interesting and important because it is the oldest seemingly reliable uranium-series age estimate yet available for the Pleistocene terrace deposits of the bay region. If valid, the age estimate suggests that the Accomack beds and equivalent strata on both sides of the Chesapeake Bay record a major high stand of the sea considerably older than that represented by the type beds of the Norfolk Formation of Oaks and Coch.

Coral sample C-4 consists of large unabraded fragments of a branching coral, *Oculina* sp., from a shallow pit dug in the Accomack beds west of Chincoteague, Va. (pl. 1, fig. 5, loc. 3). A preliminary analysis of part of this sample (C-4a, table 1) yielded excess ^{230}Th with respect to ^{234}U. Subsequently, another part of the same sample (C-4b) was crushed to small fragments and scrubbed ultrasonically in water; the analysis yielded an apparent ^{230}Th age of 341,000+137,000−66,000 years

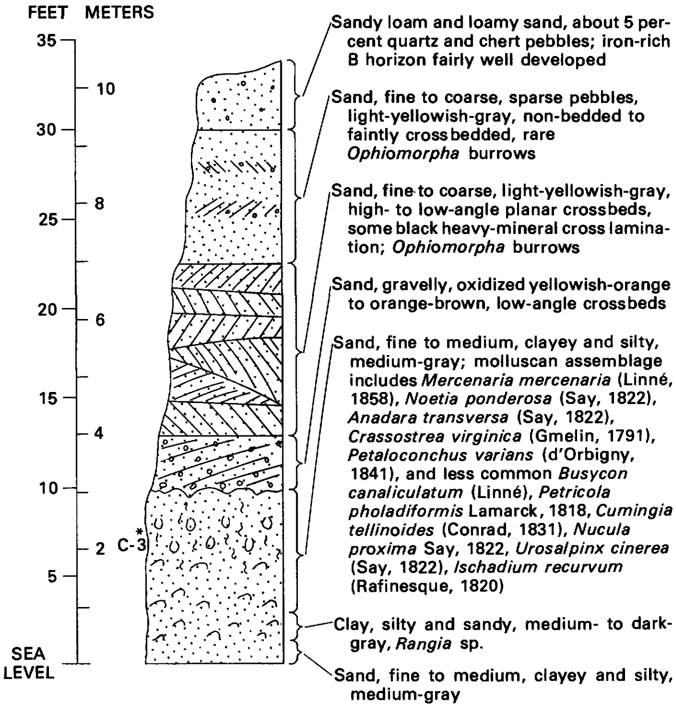


FIGURE 4.–Composite section of upper Pleistocene deposits exposed in wave-cut cliffs along the north side of Rappahannock River estuary between Norris Bridge and Cherry Point, Va. The section represents a single transgressive-regressive cycle and is believed to be equivalent to the Accomack beds of the Delmarva Peninsula east of the Chesapeake Bay. Asterisk shows horizon at which coral sample C-3 and mollusk sample S-29 were collected (see tables 1, 2).

B.P. However, because of the excess thorium, the calculated ^{230}Th age for this sample is not considered to be reliable. The ultrasonic scrubbing did not affect either the uranium concentration or the ^{234}U/^{238}U ratio (table 1). Thus, if based solely on the uranium isotopic activity ratio of 1.06, the estimated age for coral sample C-4b would be identical with that of sample C-3 (about 184,000 ± 20,000 years B.P.).

QUAHOG SAMPLES

Fourteen quahog samples of varying preservation were collected from widely scattered localities in the bay area. The estimated ages listed for most samples are averages of the calculated ^{230}Th and ^{231}Pa ages (table 2). ^{231}Pa/^{235}U ratios were not obtained for a few samples, and the age estimate is the same as the calculated ^{230}Th age. A scatter diagram shows a group of six younger ages ranging from about 24,000 to 64,000 years B.P. and a second group of eight older ages ranging from about 107,000 to 139,000 years B.P. (fig. 6). In general, the two groups of ages correspond fairly well to the groupings of "older" and "younger" Pleistocene deposits from which the samples were collected (see pl. 1, fig. 3). Several exceptions to this generalization are discussed in the text that follows.

OLDER AGE ESTIMATES

Quahog samples yielding older age estimates are mainly from the Accomack beds and equivalent strata in the Delmarva area and from unnamed fossiliferous beds exposed at Wailes Bluff, Md. and along the lower Rappahannock River estuary (pl. 1, locs. 4-7, 14, 15).

Two of the better preserved quahog samples consist of articulated *Mercenaria* collected from spoil from borrow pits dug in the Accomack beds (samples S-10 and S-12; see pl. 1, locs. 4, 5). Although sample-sediment relationships could not be observed in outcrop, the fact that the shells were articulated and unabraded seems to exclude the possibility of reworking from older deposits. Estimated ages of 113,000 years B.P. (S-12, fig. 5) and 118,500 years B.P. (S-10) are in close agreement. However, the age estimate for sample S-10 is an average of very discordant ^{230}Th and ^{231}Pa ages (see table 2) and is not considered reliable.

Two additional quahog samples from the southern Delmarva peninsula (S-20, S-21; pl. 1, locs. 7, 6) that yielded slightly older age estimates consist of shell fragments washed from borehole samples. As the correlation of the enclosing deposits is as yet uncertain, the reliability of age estimates based on these samples cannot be evaluated. If valid, however, the estimated ages of 122,000 ± 10,000 years B.P. and 128,000 ± 1,000 years B.P. would suggest approximate age equivalency with the Accomack beds.

On the west side of Chesapeake Bay, unnamed fossiliferous beds of marginal marine and estuarine origin that crop out in wavecut cliffs along the lower Rappahannock River (loc. 14) are correlated with the Accomack beds on the basis of stratigraphic and geomorphic similarities. (Stratigraphic sections of the Accomack beds and the Rappahannock River deposits appear to constitute a single transgressive-marine sequence, and each unit underlies depositional surfaces ranging from about 12 to 15 m (40 to 50 ft) in altitude.) At the Rappahannock River site, an especially well-preserved articulated *Mercenaria* (S-29) was collected from the same fossil bed as coral sample C-3 (see fig. 4 and discussion under "Coral samples"). The calculated ^{230}Th ages of 139,000 ± 10,000 years B.P. from the *Mercenaria* and 184,000 ± 20,000 years B.P. from the coral provide the only direct comparison of uranium-series coral and quahog ages presently available for the older Pleistocene deposits of the bay region.

The classic exposures of Pleistocene fossil beds at Wailes Bluff, Md. (pl. 1, loc. 15; fig. 7), near the mouth of the Potomac River estuary, have been studied intermittently for many years (Mansfield, 1928; Blake, 1953;

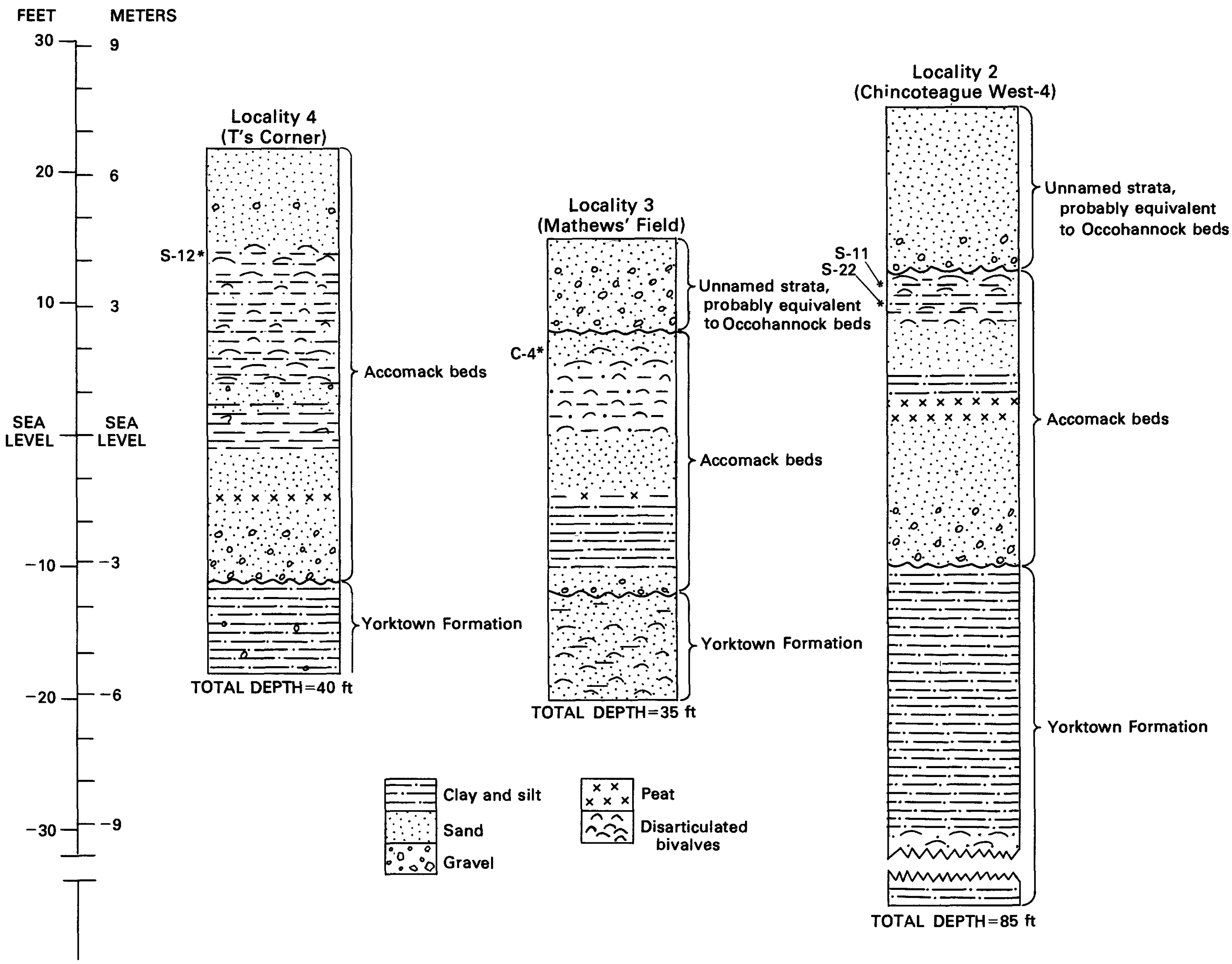


FIGURE 5.–Sections of Accomack beds from boreholes at T's Corner, Mathews' Field, and CW–4 localities, Delmarva Peninsula near Chincoteague, Va. Asterisks show approximate horizon at which samples of mollusks and corals were collected for uranium-series dating. Sample numbers refer to tables 1–3. Coral sample C–4 is from a shallow pit dug at site of Mathews' Field borehole. Locality numbers refer to plate 1.

TABLE 2.—*Analytical data and uranium-series ages of quahogs from the Chesapeake Bay area, Virginia and Maryland*

Sample[1] No.	Locality[2] No.	Stratigraphic unit	Uranium (ppm)	Thorium (ppm)	Isotopic-activity ratios $^{234}U/^{238}U$	Isotopic-activity ratios $^{230}Th/^{234}U$	Isotopic-activity ratios $^{230}Th/^{232}Th$	Isotopic-activity ratios $^{231}Pa/^{235}U$	Calculated age (10³ years B.P.) ^{230}Th[3]	Calculated age (10³ years B.P.) ^{231}Pa[4]	Estimated age (10³ years B.P.)
S-2	11. Womack pit, Va.	Norfolk Formation.	[5]0.248±.002	[5]0.0066±.0007	1.13±.02	0.445±.027	57.	0.75±.05	62±5	65±8	63.5±1.5
S-4	9. Toy Avenue pit, Va..	Norfolk Formation (?).	[5].490±.005	[5].032 ±.001	1.19±.02	.385±.015	21.	Not done	51±3	Not done	51±3
S-7	15. Wailes Bluff, Md.	Wailes Bluff deposits.	[5].314±.003	[5].085 ±.002	1.21±.02	.699±.042	9.5	.90±.04	118±12	106^{+26}_{-17}	112±6
S-8	do	do	[5].093±.001	[5].013 ±.003	1.18±.02	.651±.033	17.	.98±.08	107±9	>107	107±9
S-10	5. Parksley, Va.	Accomack beds(?).	[5]1.09 ±.01	[5].082 ±.004	1.31±.02	.807±.040	42.	.81±.40	159±16	78±10	118.5±40.5
S-11	2. Chincoteague West Quadrangle, Va.	Accomack beds.	[5]1.26 ±.01	.082 ±.008	1.15±.02	.23 ±.02	12.	.36±.01	21±2	28±3	24.5±3.5 (disregarded)
S-12	4. T's Corner, Va.	do	[5].370±.004	[8].047 ±.005	1.27±.02	.722±.029	22.	.88±.05	127±8	99^{+26}_{-17}	113±14
S-14	8. Cape Center, Va.	Nassawadox beds.	[5]1.88 ±.02	[5].05 ±.01	1.14±.02	.455±.018	59.	.71±.03	64±3	58±6	61±3
S-20	7. Bell Neck, Va.	Accomack beds (?).	[5].355±.004	[5].11 ±.01	1.22±.02	.73 ±.011	8.7	.94±.04	128±11	127^{+39}_{-20}	128±1
S-21	6. Scarborough Neck, Va.	(?)	[5]1.52 ±.02	[5].046 ±.002	1.17±.02	.661±.026	77.	.94±.04	112±8	132^{+47}_{-23}	122±10
S-25	10. New Light pit, Va.	Norfolk or Kempsville Formations.[7]	[5].154±.002	[5].011 ±.002	1.14±.02	.329±.020	16.	Not done	42±3	Not done	>45
S-26	do	do	.249±.002	.034 ±.001	1.12±.02	.297±.018	7.4	Not done	35±3	Not done	>45
S-29	14. Norris Bridge, Va.	Rappannock River deposits.	[6].222±.004	[6].021 ±.004	1.23±.02	.748±.030	23.	Not done	139±10	Not done	139±10
S-30	13. Williams pit, Va.	Tabb Formation[8] (Sedgefield Member).	[6].414±.008	[6].074 ±.007	1.17±.02	.709±.028	14.	Not done	124±9	Not done	124±9 (disregarded)

[1] Samples are *Mercenaria mercenaria* or *M. campechiensis.*
[2] Number refers to pl. 1.
[3] Corrected for unsupported ^{230}Th: $(^{230}Th)_0 = 0.67\ ^{232}Th\ e^{-\lambda^{230}t}$; calculated using half-lives of ^{230}Th and ^{234}U of 75,200 and 244,000 years, respectively.
[4] Corrected for unsupported ^{231}Pa: $(^{231}Pa)_0 = 0.67\ ^{232}Th\ e^{-\lambda^{231}t}$; calculated using half-life of ^{231}Pa of 32,500 years.
[5] Determined by mass spectrometry; reported as CaO.
[6] Determined by alpha spectrometry; reported as CaO.
[7] Of Oaks and Coch (1973).
[8] Of Johnson (1976).

Thompson, 1972). Because of geographic isolation, correlations between the Wailes Bluff deposits and the better known sections in the Delmarva Peninsula and Norfolk, Va., areas have always been speculative. Our quahog samples S-8 and S-7, yielding estimated ages of 107,000±9,000 years and 112,000±6,000 years B.P., respectively, were collected from the lower part of the Wailes Bluff section. The estimated ages suggest that the *Mercenaria* beds, which are just below the unconformity suggested by Mansfield (1928, p. 130; fig. 7, this paper), are correlative with the Accomack beds and the sections on the lower Rappahannock River estuary.

Quahog sample S-30 (loc. 13) is a highly leached articulated specimen obtained from the Tabb Formation of Johnson (1976), a sand unit in the Williamsburg, Va., area that is considered to be stratigraphically above and thus younger than the type beds of the Norfolk Formation. The calculated age of 124,000 years B.P. for sample S-30 is in direct conflict with the coral ages obtained from the Norfolk beds and is considered to be spurious. The fossil bed at the collecting site is within the zone of root penetration and has only a thin cover of very permeable sandy material. The anomalous age may be related in some manner to the high degree of leaching to which the fossils at this site have been subjected.

YOUNGER AGE ESTIMATES

Quahog samples yielding younger age estimates are mainly from the southernmost part of the Chesapeake Bay area (see fig. 6, cluster of younger ages; and pl. 1, locs. 8-11). One very anomalous age of 24,500±350 years B.P. was obtained from sample S-11 from the older Pleistocene deposits (Accomack beds, loc. 2) in the central Delmarva area. This age is clearly much too young and is, henceforth, disregarded.

The four quahog samples from the Norfolk area (S-2, S-4, S-25, S-26) were obtained from outcrops in large commercial borrow pits excavated in the type area of the Norfolk and Kempsville Formations of Oaks and Coch (1973). Samples S-2 and S-4 from the Norfolk beds yielded ages of 63,000±1,500 years and 51,000±3,000 years B.P., respectively. The age for quahog sample S-2 is in very close agreement with the estimated age for coral sample C-1 collected from the Norfolk beds at the same locality (table 2, fig. 1). Samples S-25 and S-26, yielding ^{230}Th ages of 42,000±3,000 years and 35,000±3,000 years B.P., were collected by D. F. Belknap (University of South Florida) from the Norfolk and (or) Kempsville beds exposed in a borrow pit near the community of New Light,

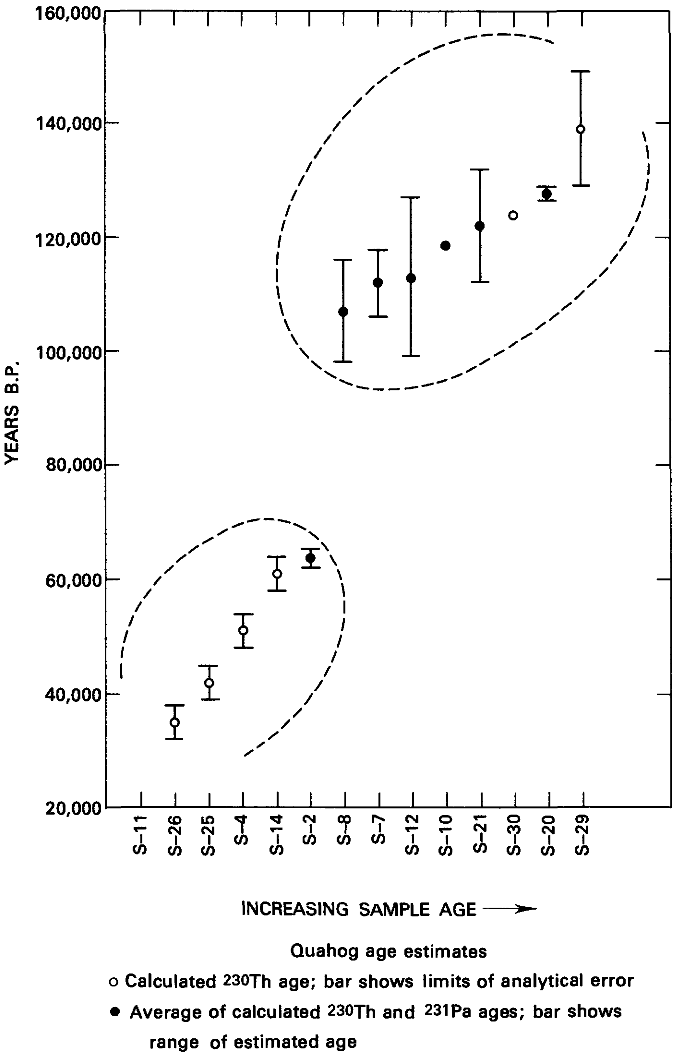


FIGURE 6.–Estimated uranium-series ages from fossil quahogs, Virginia and Maryland. Sample numbers refer to table 2.

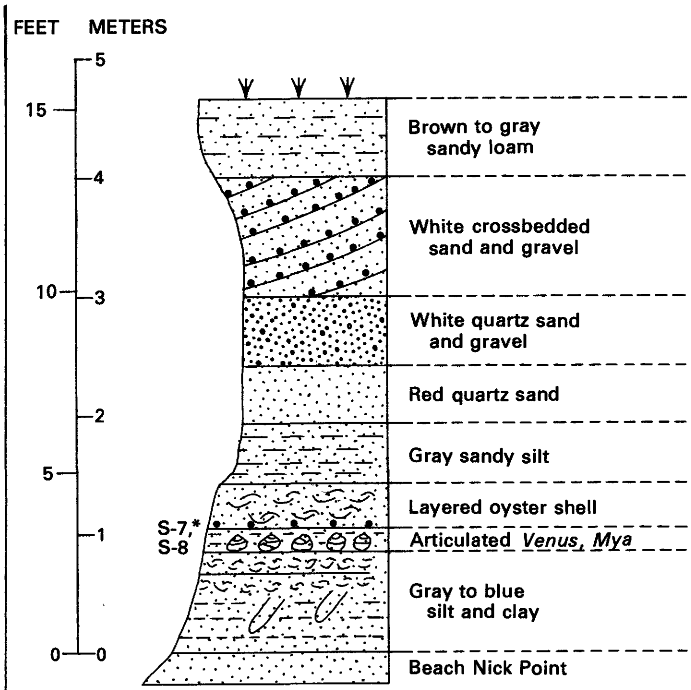


FIGURE 7.–Section of Pleistocene deposits exposed in wave-cut cliffs on the Potomac River, Wailes Bluff, Md. (modified from Thompson, 1972). Asterisk shows approximate horizon at which samples were collected. Sample numbers refer to table 2.

Va. (fig. 1). However, the uranium-series age for coral sample C-2 and radiocarbon ages of >45,000 years B.P. on wood from the Kempsville beds at this locality (U.S.G.S. radiocarbon laboratory samples W-3837 and W-3838) indicate that the uranium-series age estimates for samples S-25 and S-26 are too young.

OYSTER, GASTROPOD, AND BONE SAMPLES

The few uranium-series ages obtained from the analysis of fossil oysters do not show well-defined clustering as do the quahog ages (compare fig. 6 with 8). However, the calculated ages from oyster samples from the Omar Formation and Wailes Bluff deposits (table 3, samples S-6, S-13, S-17) do fall within the same time span as that encompassed by quahog ages from the same and equivalent units (Accomack beds and Rappahannock River deposits; see table 2). On the other hand, ages of 101,000±9,000 years and 88,000±5,000 years B.P. from oyster samples S-3 and S-5 from the Norfolk beds of the type area are considerably older than age estimates from corals and quahogs from the Norfolk (fig. 1; tables 1, 2). An age estimate of 78,500±3,500 years B.P. from the porpoise vertebra (sample B-36, table 3), obtained from the basal gravelly sands of the Kempsville, agrees more closely with coral ages from the Norfolk than do age estimates from the oysters.

AGE OF DEPOSITS

NORFOLK BEDS OF TYPE AREA AND YOUNGER ROCK-STRATIGRAPHIC UNITS

Most workers have considered the type Norfolk beds and younger deposits to be the result of deposition during and (or) after the high stand(s) of the sea associated with the last major interglacial period (the Sangamon or oxygen-isotope stage 5). This conclusion is based on (1) the moderate degree of weathering and soil development of these units, (2) the similarity of fossil assemblages to modern marine faunas, and (3) uranium-series ages from the type Norfolk beds ranging from 62,000 to

TABLE 3.—*Analytical data and uranium-series ages of oysters, gastropods, and bone from the Chesapeake Bay area, Virginia, Maryland, and Delaware*

Sample[1] No.	Locality[2] No.	Stratigraphic unit	Uranium (ppm)	Thorium (ppm)	Isotopic-activity ratios				Calculated age (10^3 years B.P.)		Estimated age (10^3 years B.P.)
					$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	$^{231}Pa/^{235}U$	^{230}Th[3]	^{231}Pa[4]	
S-3	11. Womack pit, Va.	Norfolk Formation (?).	[5]0.888 ± .009	[5]0.156 ± .008	1.12 ± .02	0.666 ± .027	13.	0.87 ± .04	110 ± 7	92 ± 15	101 ± 9
S-5	9. Toy Avenue pit, Va.	do	[5]2.85 ± .03	[5].083 ± .002	1.14 ± .02	.565 ± .023	67.	Not done	88 ± 5	Not done	88 ± 5
S-6	15. Wailes Bluff, Md.	Wailes Bluff deposits.	[5].114 ± .001	[5].12 ± .02	1.22 ± .02	.781 ± .039	3.5	.96 ± .06	133 ± 12	>102	133 ± 12
S-9	do	do	[5].101 ± .001	[5].07 ± .01	1.25 ± .02	.597 ± .036	3.3	.78 ± .06	85 ± 7	68 ± 12	76.5 ± 8.5
S-13	1. Roadcut near Frankford, Del.	Omar Formation.	[5].224 ± .002	[5].168 ± .003	1.18 ± .04	.696 ± .042	3.3	.95 ± .04	109 ± 11	129^{+85}_{-15}	119 ± 10
S-17	15. Wailes Bluff, Md.,	Wailes Bluff deposits.	[5].092 ± .001	[5].126 ± .002	1.25 ± .02	.780 ± .039	2.2	Not done	122 ± 10	Not done	122 ± 10
S-22	2. Chincoteague West Quadrangle, Va.	Accomack beds.	[5]1.31 ± .01	[5].363 ± .007	1.12 ± 02	1.12 ± .04	14.	1.13 ± .05	Not applicable.	Not applicable.	None
B-36	11. Womack pit, Va.	Kempsville Formation.[6]	[7]15.2 ± .2	[7]1.33 ± .07	1.08 ± .02	.543 ± .027	20.	.80 ± .05	82 ± 5	75 ± 10	78.5 ± 3.5

[1] Samples 3, 5, 6, 13, 17, and 22 are *Crassostrea virginica,* sample S-9 is *Busycon* sp., sample B-36 is a porpoise vertebra; all oysters are greater than 99 percent calcite.
[2] Number refers to plate 1.
[3] Corrected for unsupported ^{230}Th:$(^{230}Th)_0 = 0.67\ ^{232}Th\ e^{-\lambda_{230}t}$; calculated using half-lives of ^{230}Th and ^{234}U of 75,200 and 244,000 years, respectively.
[4] Corrected for unsupported ^{231}Pa:$(^{231}Pa)_0 = 0.67\ ^{232}Th\ e^{-\lambda_{231}t}$; calculated using half-life of ^{231}Pa of 32,500 years.
[5] Determined by mass spectrometry, reported as CaO.
[6] Of Oaks and Coch (1973).
[7] Determined by alpha spectrometry.

86,000 years B.P. (Oaks, 1964; Valentine, 1971; Oaks and Coch, 1973; Owens and Denny, 1978, 1979a, b). Our uranium-series ages of 62,000 ± 2,000 yrs, 73,000 ± 4,000 yrs, and 79,000 ± 5,000 years B.P. are in close agreement with the coral dates previously reported by Oaks and Coch and appear to confirm a late Pleistocene age for the type Norfolk.

We would like to point out, however, that the estimated age of about 71,000 ± 7,000 yrs for the Norfolk (an average of our three coral dates) is based on "closed system" assumptions. How closely does this apparent age approximate the "true" age of the Norfolk deposits? The following line of evidence suggests that the apparent uranium-series age of 71,000 yrs B.P. may be as much as several tens of thousands of years too young.

Several distinct episodes of erosion and deposition and fluctuations of sea level, recorded by the Kempsville–Sedgefield–Occohannock and Sand Bridge–Lynnhaven–Poquoson–Kent Island depositional sequences and associated scarps, took place after Norfolk time and before the last glacial maximum at 15,000 to 18,000 years B.P. In the Norfolk area, for example, the older of the post-Norfolk sequences (Kempsville beds) is separated from the type Norfolk beds by an erosional unconformity (see fig. 1). Bones of walrus and immature gray seal (*Halichoerus grypus* Fabricius) and gannet (*Morus bassanus* (Linnaeus)) in gravelly deposits just above the unconformity strongly suggest that warm-temperate climatic conditions existing during most of Norfolk and Kempsville time were interrupted by a climatic interval cold enough to cause the displacement of cold-temperate to subarctic faunas south at least as far as Norfolk, Va. (Ray and others, 1968). An assumed "true" age for the Norfolk of about 71,000 ± 7,000 yrs B.P., in conjunction with a minimum age of >45,000 years for the Kempsville beds (see USGS radiocarbon laboratory samples W-3837 and W-3838)[5], would restrict the deposition of the type Norfolk beds and the Kempsville, and the formation of the intervening unconformity, to a time interval of less than about 40,000 years. Also implied are fluctuations of sea level from (1) a high stand of as much as 10(?) m (relative to present sea level) during deposition of the type Norfolk beds, to (2) a low stand at about present sea level, or below, during formation of the erosional unconformity at the base of the Kempsville, to (3) a subsequent high stand at about 7-9 m during Kempsville time (Oaks and Coch, 1973). Although this sequence of events could possibly take place within a 40,000-year time span, it seems highly unlikely that both the Norfolk and Kempsville high stands of the sea took place in the interval from 45,000 to 85,000 years B.P. (compare global sea-level models based on oxygen-isotope data for the same time span; see papers by Shackleton and Opdyke, 1973, and other workers). No uranium-series age estimates are available for the younger Sand Bridge–Lynnhaven–Poquoson–Kent Island sequence, which probably represents either a prolonged stillstand or minor transgression of the sea to altitudes of +3 to +5 m relative to present sea level.

ACCOMACK AND RAPPAHANNOCK RIVER BEDS AND "NORFOLK" BEDS WEST OF SUFFOLK SCARP

The age of the oldest depositional sequence, comprising the Accomack, Omar, and Rappahannock River beds

[5]Samples W-3837 and W-3838 are wood from logs in the middle to upper part of the Kempsville section exposed in the New Light pit (pl. 1, loc. 10; see also fig. 1).

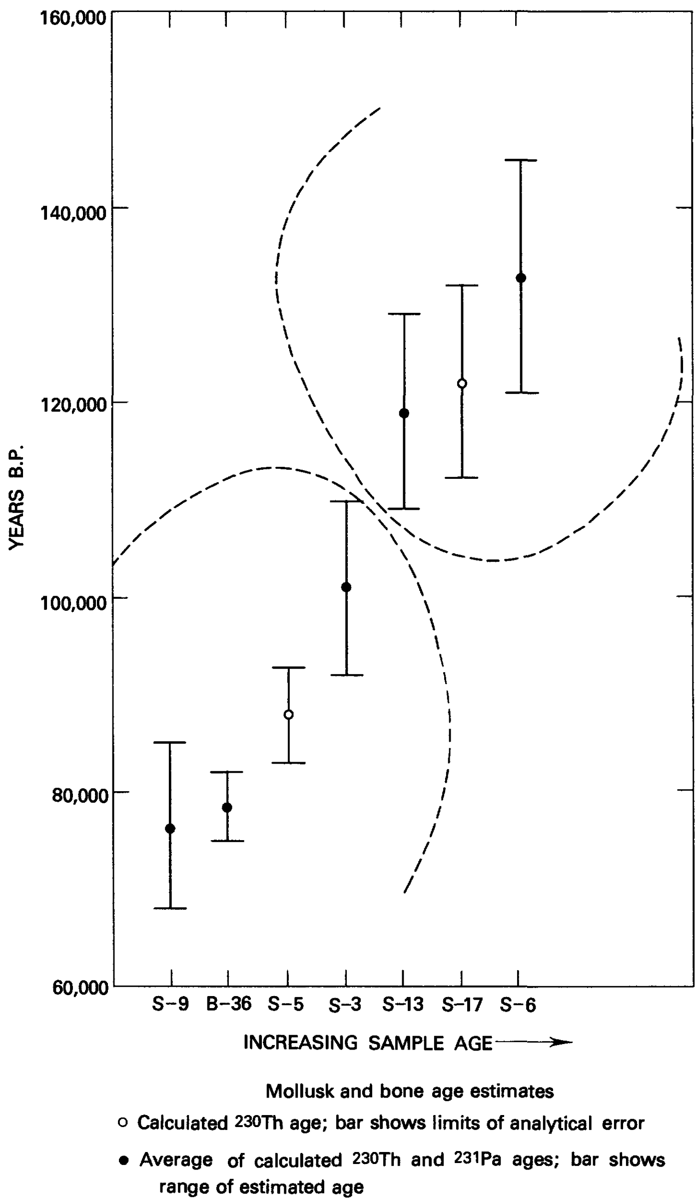


FIGURE 8.—Estimated uranium-series ages from fossil oyster, gastropod, and bone samples, Virginia, Maryland, and Delaware. Sample numbers refer to table 3.

and the "Norfolk" beds west of the Suffolk scarp, has been much more controversial than the ages of the type Norfolk beds and younger units. Because of only small differences between the faunal assamblage in the older sequence and that of the type Norfolk beds (J. Hazel, oral commun., 1973) and because of several uranium-series ages ranging from about 105,000 to 130,000 years B.P. from *Mercenaria* sp., the Accomack and Omar beds have been thought to be older than the type Norfolk but also of late Pleistocene age (Mixon and others, 1974; Owens and Denny, 1978, 1979a, b).

On the other hand, amino-acid-racemization dating of samples from the Accomack beds near Chincoteague, Va. (pl. 1, loc. 2, 3), yields age estimates of >1,300,000 years (Belknap, 1979, p. 215), thereby suggesting an early rather than late Pleistocene age for the Accomack beds at these localities. In addition, amino-acid age estimates for the Accomack beds at T's Corner (pl. 1, loc. 4), beds that borehole data indicate are equivalent to the sampled beds at localities 2 and 3, range from about 520,000 to 920,000 years B.P. (Belknap, 1979, p. 218).

More recently, a study of the abundant ostracode fauna in the Accomack beds at T's Corner and a comparison of this assemblage with assemblages in lower and upper Pleistocene sections in the Carolinas suggest that the Accomack beds are younger than about 400,000±years (T. M. Cronin, written commun., 1979; Cronin and others, 1981). Paleomagnetic studies from several localities in the Accomack, including the locality yielding coral sample C-4 and some of the older amino-acid age estimates (pl. 1, locs. 3, 4), suggest that the Accomack is of Brunhes age (<0.73 million years) and, thus, support the conclusion of the paleontologic and stratigraphic studies that the Accomack beds are younger than early Pleistocene (Liddicoat and Mixon, 1980).

The uranium-series date of 184,000±20,000 years B.P. for our recently acquired coral sample C-3 from the Rappahannock River site is the only definitive estimate of absolute age presently available for the older depositional sequence. Added significance is attached to this single age because of its compatibility with the stratigraphic, paleontologic, and paleomagnetic data. If the coral date is valid, it indicates a "late middle" or "early late" Pleistocene age for the Rappahannock River beds and equivalent strata. The "late middle" Pleistocene age estimate would follow the usage of Bowen (1978) and Cronin and others (1981), who consider middle and late Pleistocene time to encompass the intervals from 0.70 to 0.128 million years and 0.128 to 0.010 million years B.P., respectively.

REGIONAL CORRELATIONS

Along the Atlantic seaboard, stratigraphic studies of upper Pleistocene marine deposits, conducted in conjunction with uranium-series dating of the enclosed carbonate materials, are concentrated in the Norfolk and Delmarva areas of Virginia, the Myrtle Beach and Charleston areas of South Carolina, and southern Florida. Although much work remains to be done before a regional stratigraphic framework is firmly established, sufficient data are available to permit some speculation regarding the correlation of deposits of latest Pleistocene age.

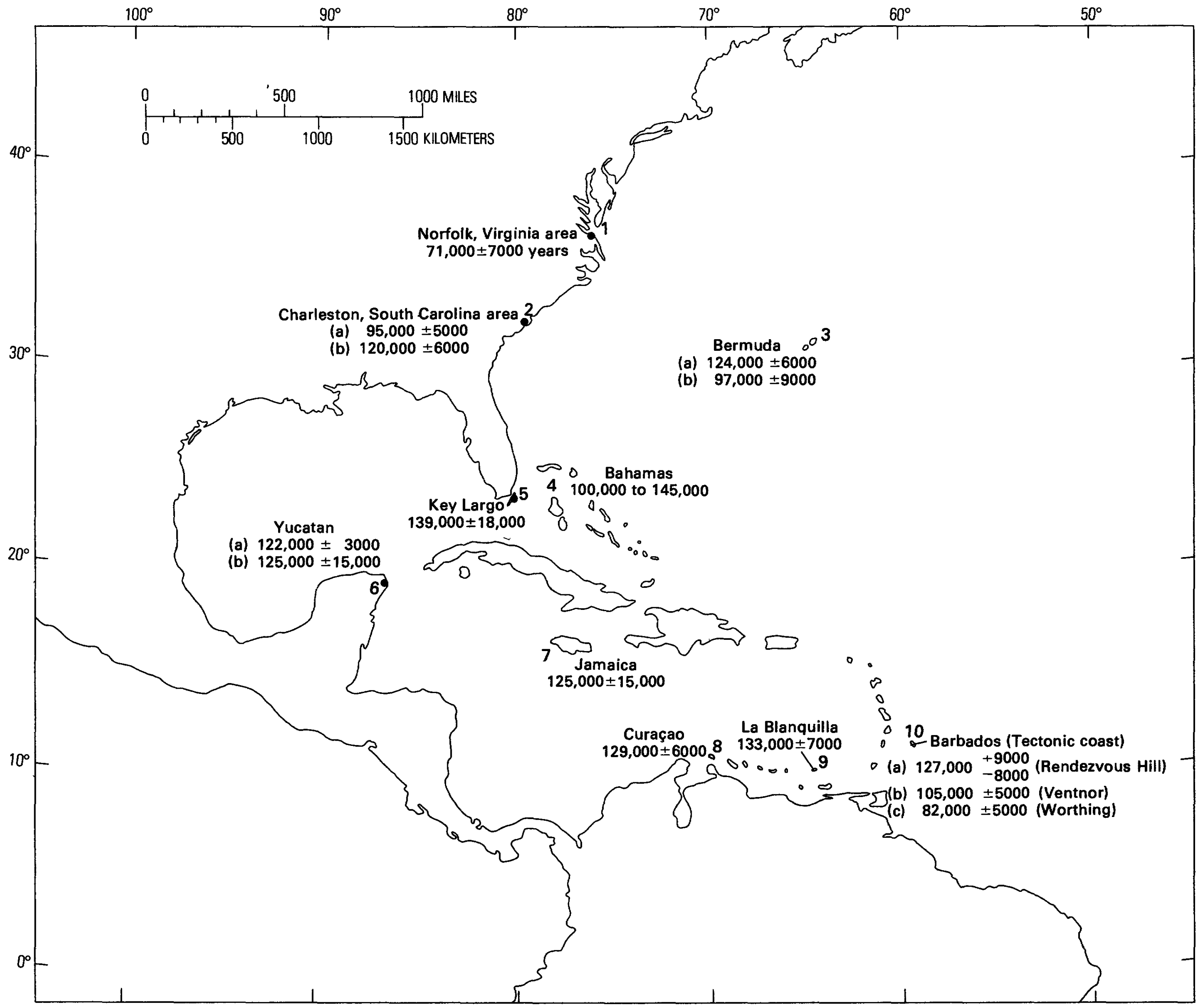
As mentioned in the preceding text, our coral ages from the type Norfolk beds and equivalent strata in the Chesapeake Bay area average about 71,000±7,000 years B.P. The fossil assemblages in these strata indicate warm-temperate climatic conditions such as are thought to have prevailed in this area during the last interglacial period (Valentine, 1971, p. D24–D25). Interestingly, the upper Pleistocene marine deposits of the outermost Coastal Plain of South Carolina yield somewhat older coral ages clustering at about 95,000 years B.P. (Cronin and others, 1981). These deposits, including the Wando beds of the Charleston area, contain fossil assemblages indicating subtropical climatic conditions. Altitudes of depositional surfaces at the top of the uppermost Pleistocene marine sequences in both the Chesapeake Bay and the South Carolina areas indicate maximum paleosea levels at about 10–12 m relative to present sea level. Also of interest is the paucity of uranium-series coral ages in the 115,000 to 135,000 years B.P. range, commonly thought to represent the last interglacial high sea stand, in both the Chesapeake Bay and South Carolina areas. We suggest that the Norfolk beds of the southern Chesapeake Bay area and the uranium-series dated deposits in the South Carolina area possibly represent the same marine transgression. In this interpretation, the differences in paleoclimate indicated by fossil assemblages in the type Norfolk beds and the marine deposits of latest Pleistocene age in South Carolina (warm temperate in the north versus subtropical in the south) simply reflect an expected latitudinal variation in climatic conditions existing during the same interval of geologic time.

The above comparison of clusters of uranium-series age estimates from the Chesapeake and South Carolina areas is based on dates from coral samples that have been subjected to at least somewhat similar syndepositional and postdepositional conditions. That is, corals in both areas grew as isolated specimens encrusting shells of mollusks and were buried by very permeable detrital deposits that have probably been water-saturated for much of the time since deposition. In contrast, most uranium-series ages from Florida and the Caribbean area are from samples from uplifted coral-reef tracts (Barbados) and coralline limestones (Key Largo).

Comparisons of uranium-series coral ages from upper Pleistocene deposits of the Chesapeake Bay area, South Carolina, Florida, and the Caribbean are extremely speculative, in part because of possible errors in correlation of deposits and variation in estimated ages for the same deposits, as determined by different laboratories (Harmon and others, 1979). However, we would like to point out an apparent increase in estimated uranium-series age, from the middle Atlantic Coastal Plain east to Bermuda and south to the Caribbean, of deposits supposedly associated with high stands of the sea during the last interglacial period (fig. 9). The range of ages shown in figure 9 suggests differences in diagenetic modification of coralline material due in part to regional differences in depositional and postdepositional environments. Important environmental factors may include temperature and duration of water saturation of deposits and thus would be affected by differing amounts of relative uplift and variable climatic conditions prevailing since the last interglacial period (see also Harmon and others, 1979, p. 409). Our speculation concerning the possible equivalency of the type Norfolk beds (apparent age=71,000±7,000 yrs), deposits of the outermost Coastal Plain in South Carolina (apparent age =95,000±5,000 yrs), and deposits in the Caribbean area thought to represent the highest stand of the sea during the last interglacial period (apparent age=125,000±10,000 yrs) will be looked on with suspicion by workers who would accept the coral age estimates unquestioningly. These workers will tend to correlate the Norfolk transgression directly with the high stand of the sea associated with oxygen-isotope stage 5a and, for example, the uplifted reef tract of Barbados Terrace I considered to have formed at about 82,000 years B.P. (Bender and others, 1979). However, the latter interpretation appears to be in conflict with stratigraphic and paleoclimatic data that suggest at least one and possibly two high stands of the sea in the post-Norfolk part of Pleistocene time (see discussion of the type Norfolk beds at beginning of previous section). Indeed, if there is in fact a correlation between the global sea-level model based on the oxygen-isotope data and paleosea levels as recorded by the terrace deposits of the southern Chesapeake Bay area, it would seem more likely that the type Norfolk beds represent the peak transgression of the last interglaciation (oxygen-isotope stage 5e). The Kempsville beds may represent a transgression of lesser magnitude (stage 5c?), and the Sand Bridge-Lynnhaven-Poquoson-Kent Island sequence a prolonged stillstand or minor fluctuation of sea level possibly associated with oxygen-isotope stage 5a (see fig. 10).

SUMMARY AND CONCLUSIONS

1. Our coral samples C–1, C–2, and C–18 from the type beds of the Norfolk Formation of Oaks and Coch have yielded uranium-series ages of 62,000±2,000, 73,000±4,000, and 79,000±5,000 years B.P., respectively. An age estimate of 71,000 years for the Norfolk beds, obtained by averaging the above ages, is in fairly close agreement with previously reported $^{230}Th/^{234}U$ coral ages from the Norfolk, which range from 62,000 to 86,000 years (Oaks and Coch, 1973).



1—*Astrangia* sp. from Norfolk Formation near Norfolk, Va. (average of 3 dates, this paper).
2a—*Astrangia* sp. from upper Pleistocene terrace deposits near Charleston, S.C. (average of 3 dates, Cronin and others, 1980).
2b—Single age estimate from deposits of uncertain correlation. On the basis of presently available borehole data, fossiliferous horizon not distinguishable from beds yielding younger age estimate (see 2a).
3a—Average of seven age estimates from 5 corals (*Diploria strigosa*) from Devonshire Member of Paget Formation.
3b—Average of four estimates from a single *Diploria strigosa* from Spencers Point Member of Paget Formation
Age estimates and geological relationships suggest two short, distinct episodes of high sea stand in Bermuda (Harmon and others, 1978).
4—Sixteen age estimates ranging from about 100,000–145,000 years B.P. with concentration of 10 ages ranging from 115,000 to 130,000 years; two possible sea-level maxima are near +5.6 m and +4.3 m, but only the high stand near 5.6 m at about 125,000 years B.P. is well documented (Neumann and Moore, 1975).
5—Average of dates from 13 laboratories of in situ coral head from Key Largo Limestone (Harmon and others, 1979).
6a—Average of 5 dates from coral heads (*Diploria* sp. and *Monastrea* sp.) from strand-plain limestones of eastern Yucatan Peninsula and Cozumel Island (Szabo and others, 1978).
6b—One age estimate from *Monastrea* sp. from near Akumal, Yucatan Peninsula (Ward and Wilson, 1976).
7—Age estimate from samples from Falmouth Formation (Moore and Somayajulu, 1974).
8—Average of 5 age estimates from *Diploria*, *Monastrea*, and *Acropora* (Schubert and Szabo, 1978).
9—Average of 2 age estimates from *Monastrea* sp. and an unidentified sample (Schubert and Szabo, 1978).
10a—Age estimate from samples of *Acropora* sp. from Terrace III (Rendezvous Hill) of Barbados (Bender and others, 1979).
10b, c—Age estimates from Terrace II (Ventnor) and Terrace I (Worthing), respectively, thought to have formed during high sea stands that were lower than today's sea level.

FIGURE 9.—Map showing variation in estimated uranium-series coral ages for deposits thought to represent high stands of the sea associated with the last interglacial period. Increase in apparent age of deposits considered to represent peak transgression (oxygen-isotope stage 5e) from the Norfolk area, Virginia, southward to the Caribbean and eastward to Bermuda suggests possible regional differences in diagenetic modification of coralline material.

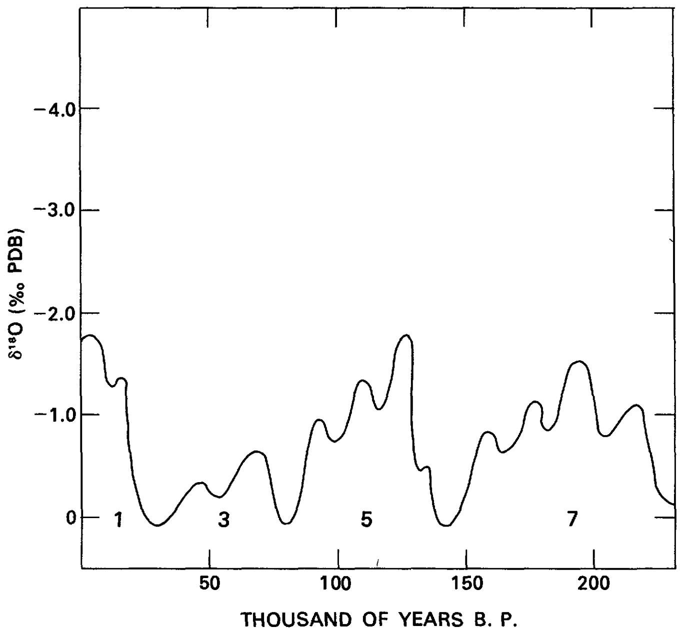


FIGURE 10.–Generalized oxygen-isotope curve for isotope stages 1-8 (modified from Fairbanks and Mathews, 1978; based on generalized curve of Emiliani, 1972; with time scale from Broecker and van Donk, 1970). Peaks of curve are interpreted to coincide in time with high stands of the sea. Isotope stage 5, associated with a general high sea-level stand during the last interglacial period, is commonly divided into substages 5a, 5b, 5c, 5d, and 5e.

2. An age of 184,000±20,000 years B.P. from coral sample C–3 from fossil beds near the mouth of the Rappahannock River is the oldest reliable uranium-series age estimate yet available for Pleistocene deposits in the Chesapeake Bay region. This age contrasts with an older but less reliable $^{230}Th/^{234}U$ age of 341,000+139,000−66,000 years B.P. from coral sample C–4b from the Accomack beds directly across the bay. However, if coral samples C–3 and C–4b are compared on the basis of the $^{234}U/^{238}U$ activity ratios (table 1), the estimated ages are the same and are in agreement with the correlation of the Accomack beds and Rappahannock River deposits on the basis of stratigraphic and geomorphic similarities (fig. 3).
3. Calculated coral dates and age estimates for the type Norfolk beds and the Accomack beds and Rappahannock River deposits are based on closed-system assumptions and thus are "apparent" rather than "true" ages. The uranium-series age estimate of 71,000 years for the Norfolk beds is considered to be too young by as much as several tens of thousands of years on the basis of stratigraphic and geomorphic data that indicate one or more episodes of deposition and erosion associated with high sea stands in the post-Norfolk part of late Pleistocene time. The sequence of geologic events in the southern Chesapeake Bay area in post-Norfolk time (Oaks and Coch, 1973; Johnson, 1976; Mixon, unpublished data, 1974–1978) suggests that the Norfolk beds of the type locality more probably represent deposition during the peak transgression associated with the last interglacial period than a minor fluctuation of the sea near the end of the period.
4. Age equivalency of the type Norfolk beds and upper Pleistocene marine deposits in South Carolina with uranium-series ages clustering at about 95,000 years B.P. is postulated on the basis of (1) similar geomorphic position in the outermost Coastal Plain, (2) similar maximum paleosea levels, and (3) slight differences in fossil assemblages and paleoclimates such as might be expected because of latitudinal variation in climatic conditions during the same interval of geologic time.
5. If valid, our speculations concerning the possible equivalency of the type Norfolk beds (apparent age=71,000±7,000 yrs), deposits of the outermost Coastal Plain in South Carolina (apparent age=95,000±5,000 years), and deposits in the Caribbean area thought to represent the highest stand of the sea during the last interglacial period (apparent age=125,000±10,000 years) indicate considerable regional variation in uranium-series coral ages for deposits of the same geologic age (see fig. 9). The inferred variation in uranium-series ages might be accounted for, at least in part, by diagenetic modification of coralline material due to regional differences in depositional and postdepositional environments.
6. Estimated ages based on $^{230}Th/^{234}U$ and $^{231}Pa/^{235}U$ ratios from 13 fossil quahog samples (*Mercenaria* sp.) from the bay area form two distinct groups (fig. 6). After the rejection of two sample ages (S–11, S–30) because of stratigraphic conflicts, the two groups of ages correspond fairly well to the groupings of "older" and "younger" Pleistocene deposits from which the samples were collected (pl. 1; fig. 3). These data suggest that averages of multiple quahog dates from carefully selected samples may be of some use in determining the *relative* age of upper Pleistocene deposits in the bay area.
7. Age estimates based on uranium-series dating of fossil quahogs from the bay area are fairly consistently younger than age estimates based on corals from the same stratigraphic units (fig. 6; tables 1, 2). Thus, our uranium-series dates from quahogs appear to be of little value in estimations of *absolute* age of the terrace deposits.

8. The few available uranium-series age estimates based on fossil oysters do not show well-defined grouping as do the quahog ages (compare fig. 6 with 8).
9. Coral ages, in conjunction with the quahog data, suggest that the low-lying (<17 m in altitude) terrace deposits in the Chesapeake Bay area record two major transgressions of the sea in the Pleistocene. The earlier transgression, thought to have taken place in early late Pleistocene time (=oxygen-isotope stage 7?), is recorded by the Rappahannock River fossil beds, the Accomack deposits of the Delmarva Peninsula, and, possibly, the basal fossiliferous deposits at the Wailes Bluff, Md., locality. The peak marine transgression in latest Pleistocene time (=oxygen-isotope stage 5?) is represented by the type beds of the Norfolk Formation and equivalent strata in the southern bay area. The younger Kempsville–Sedgefield–Occohannock and Sand Bridge–Lynnhaven–Poquoson–Kent Island sequences probably represent minor transgressions and (or) stillstands of the sea during an overall regression at the close of the last interglacial period (fig. 10).

REFERENCES CITED

Belknap, D. F., 1979, Application of amino acid geochronology to stratigraphy of late Cenozoic marine units of the Atlantic Coastal Plain: Newark, Del., University of Delaware, Ph.D. dissertation, 550 p.

Bender, M. L., Fairbanks, R. G., Taylor, F. W.,Mathews, R. K., Goddard, J. G., and Broecker, W. S., 1979, Uranium-series dating of the Pleistocene reef tracts of Barbados, West Indies: Geological Society of America Bulletin, v. 90, no. 6, pt. I, p. I577–I594.

Blake, S. F., 1953, The Pleistocene fauna of Wailes Bluff and Langleys Bluff, Maryland: Smithsonian Miscellaneous Collections, v. 121, no. 12, 32 p.

Bowen, D. Q., 1978, Quaternary geology: Oxford, Pergamon Press, 221 p.

Broecker, W. S., and van Donk, J., 1970, Insolation changes, ice volumes, and the O^{18} record in deep-sea cores: Reviews of Geophysics and Space Physics, v. 8, no. 1, p. 169–198.

Cronin, T. M., Szabo, B. J., Ager, T. A., Hazel, J. E., and Owens, J. P., 1981, Quaternary climates and sea levels of the U.S. Atlantic Coastal Plain: Science, v. 211, no. 4479, p. 233–240.

Emiliani, Cesare, 1972, Quaternary paleotemperatures and the duration of the high-temperature intervals: Science, v. 178, no. 4059, p. 398–401.

Fairbanks, R. G., and Matthews, R. K., 1978, The marine oxygen isotope record in Pleistocene coral, Barbados, West Indies: Quaternary Research, v. 10, no. 2, p. 181–196.

Hack, J. T., 1957, Submerged river system of Chesapeake Bay: Geological Society of America Bulletin, v. 68, no. 7, p. 817–830.

Harmon, R. S., Ku, T. -L., Matthews, R. K., and Smart, P. L., 1979, Limits of U-series analysis–Phase 1 results of the Uranium-Series Intercomparison Project: Geology, v. 7, no. 8, p. 405–409.

Harmon, R. S., Schwarcz, H. P., and Ford, D. C., 1978, Late Pleistocene sea level history of Bermuda: Quaternary Research, v. 9, no. 2, p. 205–218.

James, N. P., Mountjoy, E. W., and Omura, Akio, 1971, An early Wisconsin reef terrace at Barbados, West Indies, and its climatic implications: Geological Society of America Bulletin, v. 82, no. 7, p. 2011–2017.

Johnson, G. H., 1972, Geology of the Yorktown, Poquoson West, and Poquoson East Quadrangles, Virginia: Virginia Division of Natural Resources Report of Investigations 30, 57 p.

——— 1976, Geology of the Mulberry Island, Newport News North, and Hampton Quadrangles, Virginia: Virginia Division of Natural Resources Report of Investigations 41, 72 p.

Kaufman, A., Broecker, W. S. Ku, T. -L., and Thurber, D. L., 1971, The status of U-series methods of mollusk dating: Geochimica et Cosmochimica Acta., v. 35, no. 11, p. 1155–1183.

Kraft, J. C., 1971, Sedimentary facies patterns and geologic history of a Holocene marine transgression: Geological Society of America Bulletin, v. 82, no. 8, p. 2131–2158.

Liddicoat, J. C., and Mixon, R. B., 1980, Paleomagnetic investigation of Pleistocene sediments in the Delmarva Peninsula, central Atlantic Coastal Plain [abs.]: Geological Society of America, Abstracts with Programs, v. 12, no. 2, p. 70.

Mansfield, W. C., 1928, Notes on Pleistocene faunas from Maryland and Virginia and Pliocene and Pleistocene faunas from North Carolina: U.S. Geological Survey Professional Paper 150, p. 129–140.

Mixon, R. B., Hazel, J. E., Rubin, Meyer, Sirkin, L. A., and Szabo, B. J., 1974, Geologic framework of the southernmost Delmarva Peninsula, Accomack and Northampton Counties, Virginia: Geological Society of America Abstracts with Programs, v. 6, no. 1, p. 56–57.

Moore, W. S., and Somayajulu, B. L. K., 1974, Age determinations of fossil corals using $^{230}Th/^{234}Th$ and $^{230}Th/^{227}Th$: Journal of Geophysical Research, v. 79, no. 33, p. 5065–5068.

Neumann, A. C., and Moore, W. S., 1975, Sea level events and Pleistocene coral ages in the northern Bahamas: Quaternary Research, v. 5, no. 2, p. 215–224.

Oaks, R. Q., Jr., 1964, Post-Miocene stratigraphy and morphology, outer Coastal Plain, southeastern Virginia: New Haven, Conn., Yale University, Department of Geology, [240] p. (Technical Report 5 under Contract NONR 609(40) Task Order NR 388-064, Geography Branch, Office of Naval Research).

Oaks, R. Q., Jr., and Coch, N. K., 1973, Post-Miocene stratigraphy and morphology, southeastern Virginia: Virginia Division of Mineral Resources Bulletin 82, 135 p.

Oaks, R. Q., Jr., Coch, N. K., Sanders, J. E., and Flint, R. F., 1974, Post-Miocene shorelines and sea levels, southeastern Virginia, *in* Oaks, R. Q., Jr., and DuBar, J. R., eds., Post-Miocene stratigraphy, central and southern Atlantic Coastal Plain: Logan, Utah, Utah State University Press, p. 53–87.

Owens, J. P., and Denny, C. S., 1978, Geologic map of Worcester County: Baltimore, Maryland Geological Survey, scale 1:62,500.

——— 1979a, Geologic map of Wicomico County: Baltimore, Maryland Geological Survey, scale 1:62,500.

——— 1979b, Upper Cenozoic deposits of the central Delmarva Peninsula, Maryland and Delaware: U.S. Geological Survey Professional Paper 1067–A, 28 p.

Ray, C. E., Wetmore, Alexander, Dunkle, D. H., and Drez, Paul, 1968, Fossil vertebrates from the marine Pleistocene of southeastern Virginia: Smithsonian Miscellaneous Collections, v. 153, no. 3 (Publication 4742), 25 p., 2 pl.

Rosholt, J. N., Doe, B. R., and Tatsumoto, M., 1966, Evolution of the isotopic composition of uranium and thorium in soil profiles: Geological Society of America Bulletin, v. 77, no. 9, p. 987–1004.

Rosholt, J. N., and Szabo, B. J., 1969, Determination of protactinium by neutron activation and alpha spectrometry, *in* Modern trends in activation analysis, v. 1–International Conference, Gaithersburg, Maryland, 1968, Proceedings: U.S. National Bureau of Standards Special Publication 312, v. 1, p. 327–333.

Schubert, Carlos, and Szabo, B. J., 1978, Uranium-series ages of Pleistocene marine deposits on the islands of Curaçao and La Blanquilla, Caribbean Sea: Geologie en Mijnbouw, v. 57, no. 2, p. 325–332.

Shackleton, N. J., and Opdyke, N. D., 1973, Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28-238 – Oxygen isotope temperatures and ice volumes on a 10^5 year and 10^6 year scale: Quaternary Research, v. 3, no. 1, p. 39–55.

Szabo, B. J., 1969, Uranium-series dating of Quaternary successions, *in* Ters, M., ed., Études sur la quaternaire dans le monde: Paris, International Union for Quaternary Research, 8th Congress, 1969, p. 941–949.

——— 1979, Uranium-series age of coral reef growth on Rottnest Island, Western Australia: Marine Geology, v. 29, nos. 1–4, p. M11–M15.

Szabo, B. J., and Collins, Desmond, 1975, Ages of fossil bones from British interglacial sites: Nature, v. 254, no. 5502, p. 680–682.

Szabo, B. J., Malde, H. E., and Irwin-Williams, Cynthia, 1969, Dilemma posed by uranium-series dates on archaeologically significant bones from Valsequillo, Puebla, Mexico: Earth and Planetary Science Letters, v. 6, no. 4, p. 237–244.

Szabo, B. J., and Rosholt, J. N., 1969, Uranium-series dating of Pleistocene molluscan shells from southern California – An open system model: Journal of Geophysical Research, v. 74, no. 12, p. 3253–3260.

Szabo, B. J., and Vedder, J. G., 1971, Uranium-series dating of some Pleistocene marine deposits in southern California: Earth and Planetary Science Letters, v. 11, no. 4, p. 283–290.

Szabo, B. J., Ward, W. C., Weidie, A. E., and Brady, M. J., 1978, Age and magnitude of the late Pleistocene sea-level rise on the eastern Yucatan Peninsula: Geology, v. 6, no. 12, p. 713–715.

Thompson, D. E., 1972, Paleoecology of the Pamlico Formation, Saint Marys County, Maryland: New Brunswick, N.J., Rutgers University, Ph.D. dissertation, 179 p.

Valentine, P. C., 1971, Climatic implications of a late Pleistocene ostracode assemblage from southeastern Virginia: U.S. Geological Survey Professional Paper 683-D, 28 p.

Ward, W. C., and Wilson, J. L., 1976, General aspects of the northeastern coast of the Yucatan Peninsula, *in* Weidie, A. E., and Ward, W. C., eds., Carbonate rocks and hydrogeology of the Yucatan Peninsula, Mexico: New Orleans, La., New Orleans Geological Society, p. 35–44.

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